

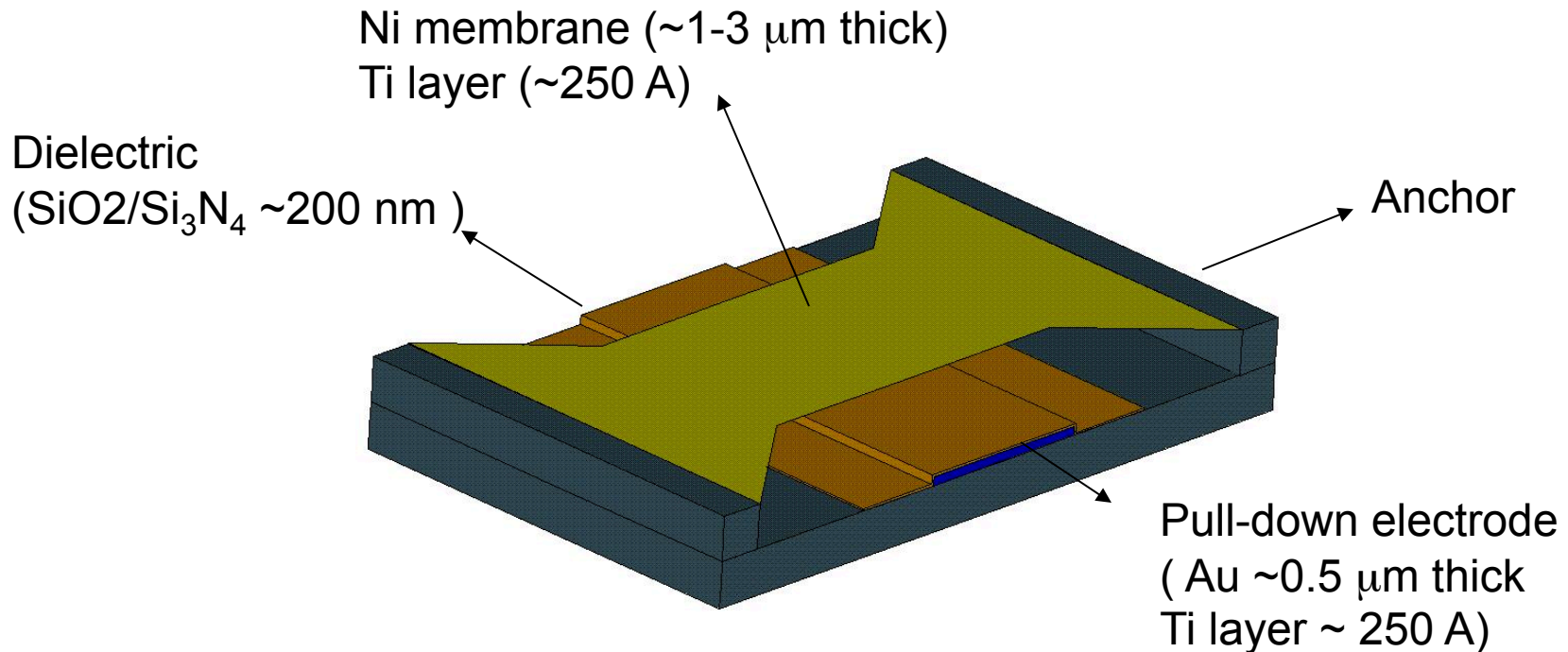


# Predictive simulation of RF MEMS

Jayathi Murthy  
Purdue University

ASC 2010 PI Meeting  
February 8-10, 2010  
Las Vegas, NV

# Target PRISM Device



- Contacting capacitive RF MEMS switch
- Used for contact actuators and capacitive switches
- Metal membrane makes periodic contact with thin dielectric layer

- Membrane
  - Length ~ 400 μm
  - Width ~ 100 μm
  - Thickness ~ 1-3 μm
- N<sub>2</sub> or air environment (~ 1 atm)
- Actuation voltage ~ 40-100V
- Hold down voltage ~ 5-15V
- Switching frequency 100 Hz-10 kHz
- Response time – 3-10 microseconds

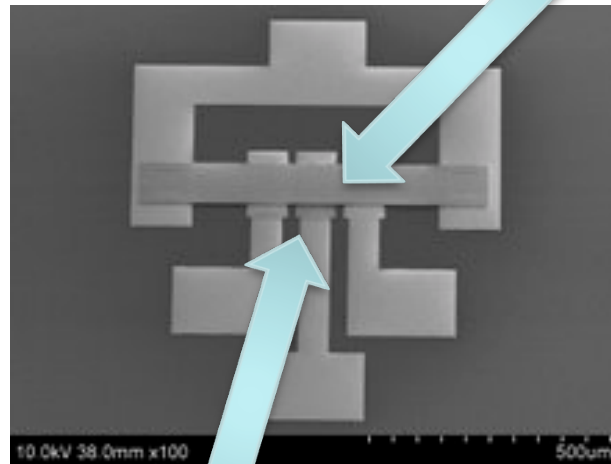
# Failure Mechanisms

## Fluid damping

Slip and rarefaction effects  
Periodic transition between continuum  
and rarefied regimes

## Creep

Microstructure and size effects,  
Grain boundaries and free surfaces  
Dislocation and grain sliding



## Dielectric charging

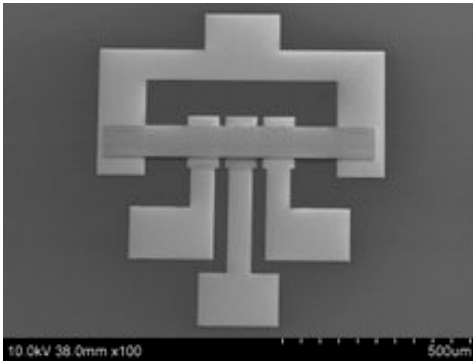
Trapped charges,  
coupled to defect generation  
and evolution

## Contact physics

Interactions between surfaces, stiction  
Sub-surface defects, surface chemistry

# Connection between Scales

Device scale



Full device simulation

- Full device simulation

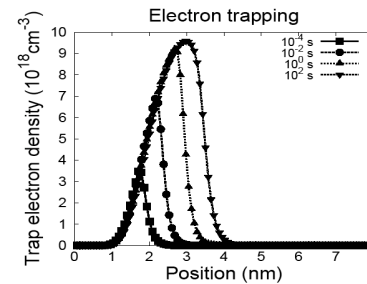
Full device simulation

- Parameters in dielectric charging model

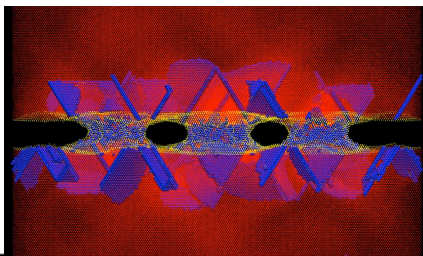
dielectric

Phase field micromechanics

- Capture individual dislocation
- Size effects emerge naturally



Atomistic scale



Atomistic simulations

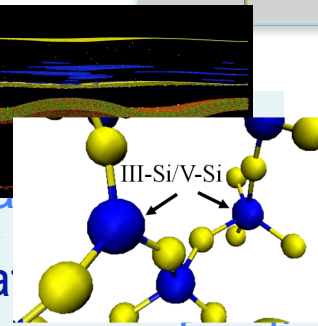
- Properties of individual dislocation
- Dislocation mobility
- Dislocation interaction

Atomistic simulation

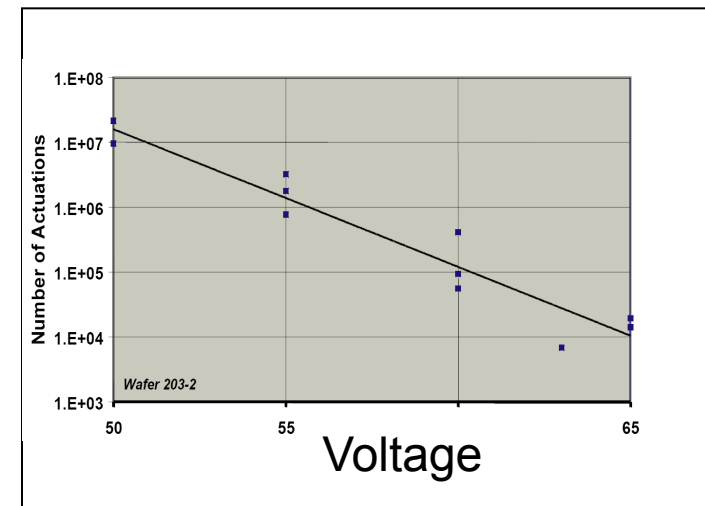
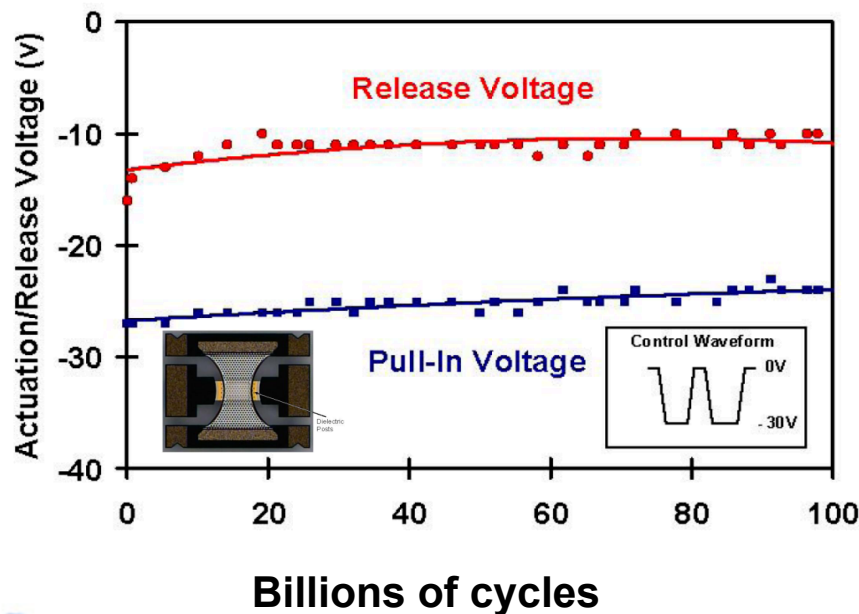
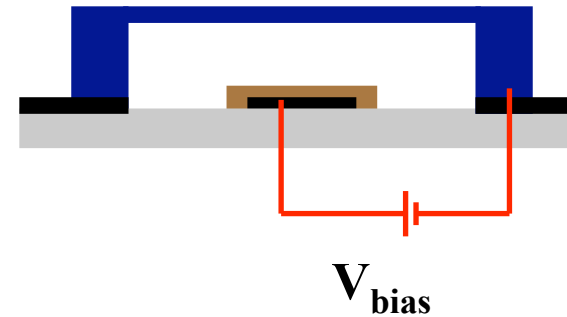
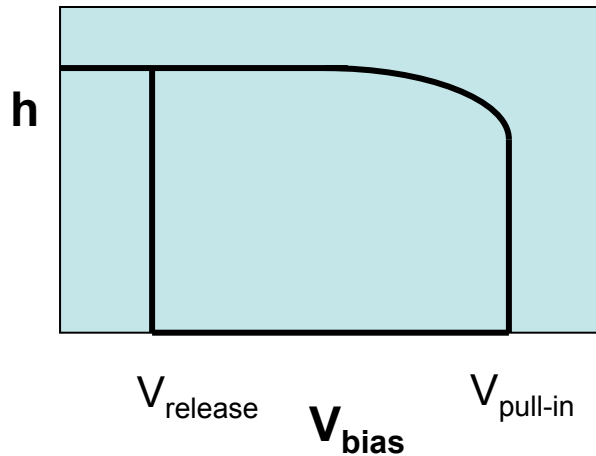
- Pull-out force as a function of contact

Atomistic simulations

- Energy levels of traps

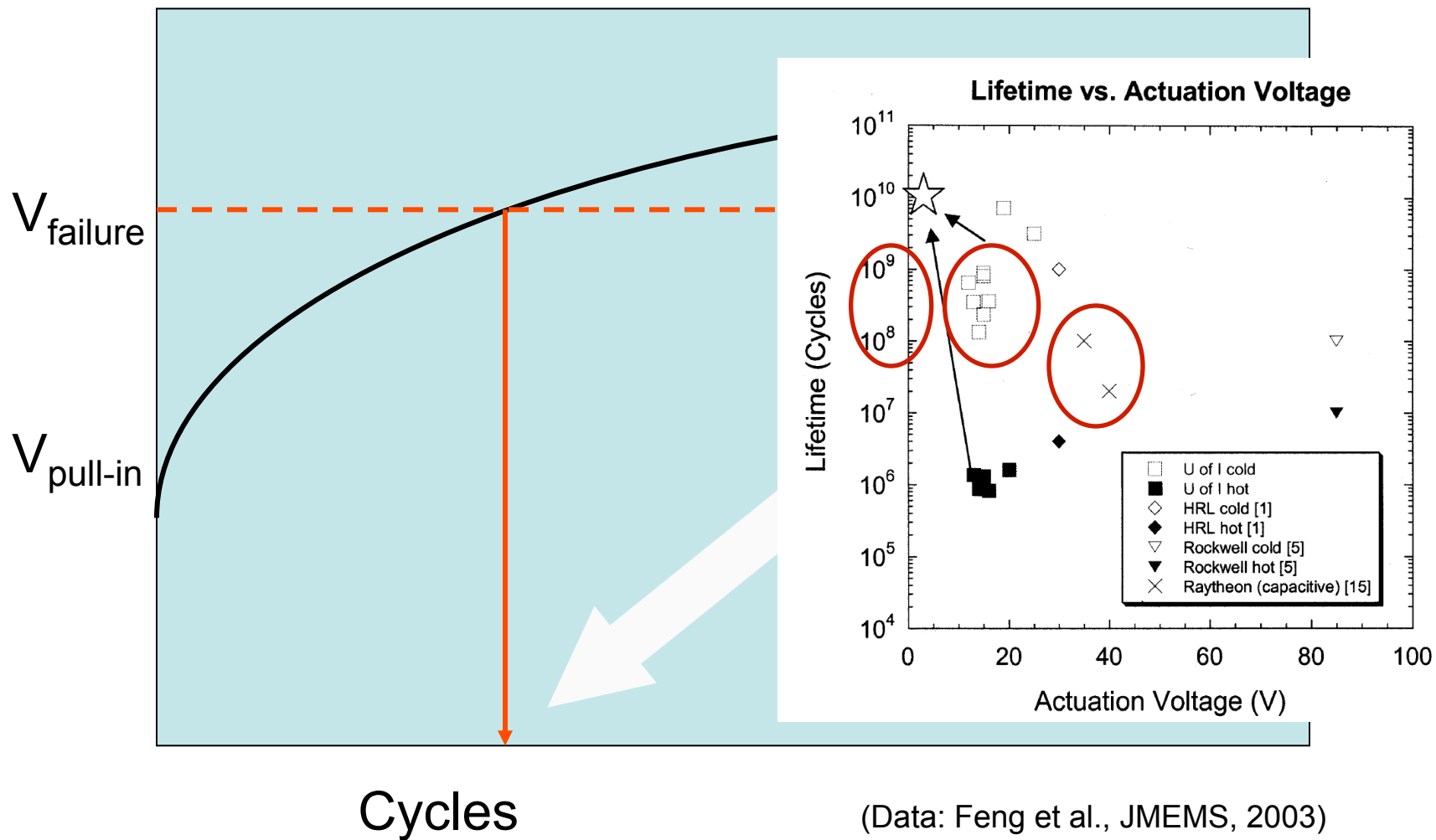


# Prediction Goal I – Lifetime Prediction under Accelerated Testing

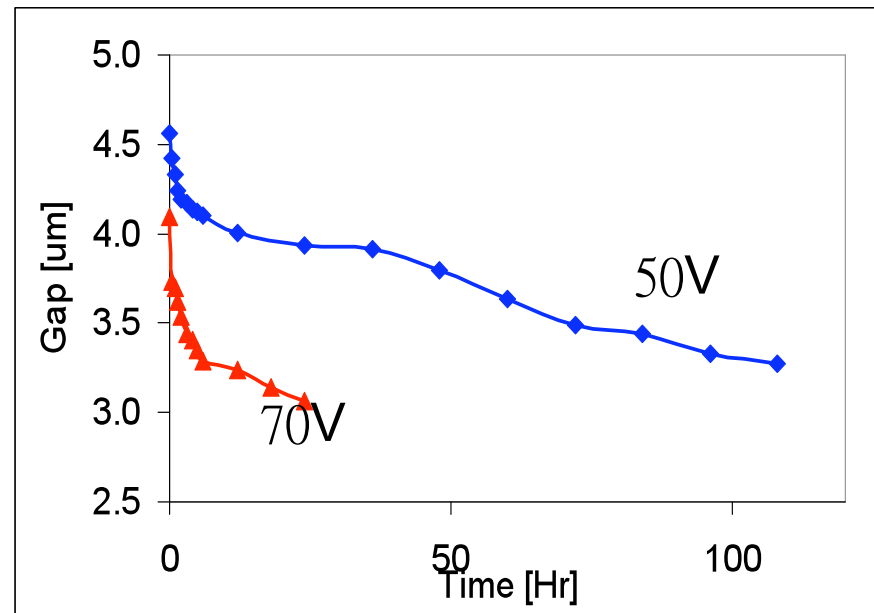


Goldsmith et al., 2001 – 2006

# Prediction Goal - I



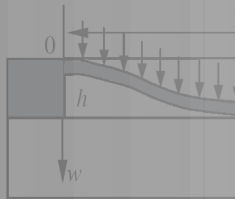
# Prediction Goal -II



- Predict the change of gap with respect to time at fixed voltage,  $V_{\text{hold}}$
- Combination of creep and dielectric charging
- Our goal is to predict critical slopes in the time-evolution of gap to with 20% mean square error with respect to experiment.

V&V a

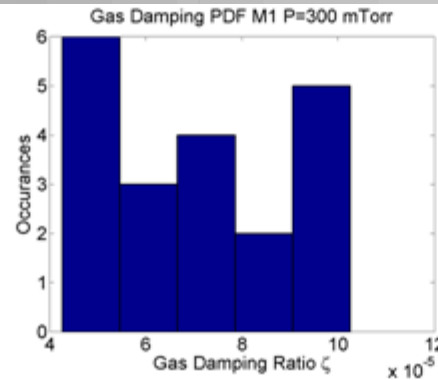
Coarse-C



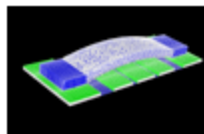
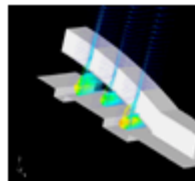
$$\rho_l \frac{\partial^2 w}{\partial t^2} = - \frac{E}{1 - \nu} \left( \frac{\partial w}{\partial x} + \frac{\partial w}{\partial y} \right)$$

- 2D membrane
- Electrostatic
- Fluid damping
- Contact and
- Dielectric ch

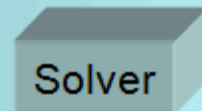
Propagate u  
determine m



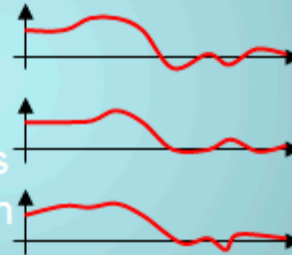
Experimental  
outputs



Stochastic Collocation Methods  
Generalized Polynomial Chaos (gPC)



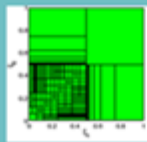
Choice of inputs  
from collocation



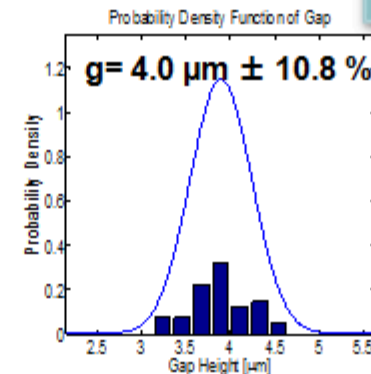
Epistemic  
uncertainties  
in outer loop

$$\frac{\partial y_f}{\partial x_l}$$

Sensitivity  
analysis



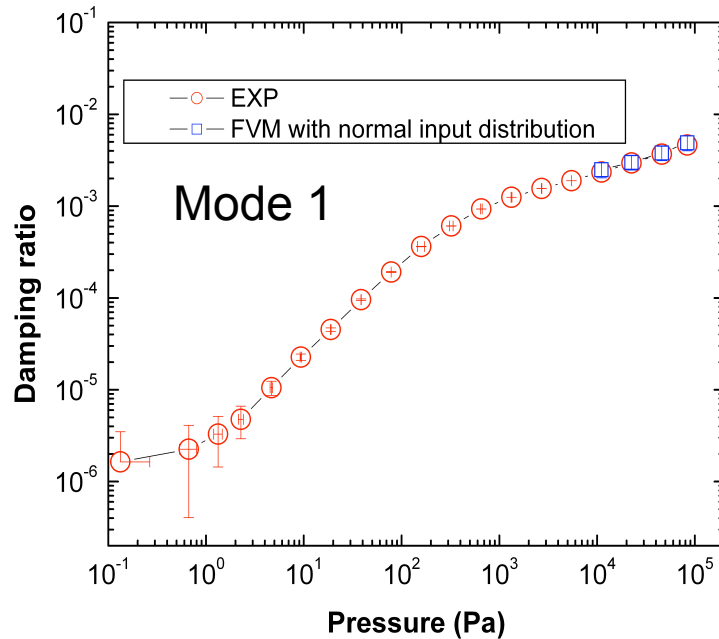
Sparse and  
adaptive  
collocation



Uncertainty  
Quantification  
for System  
Simulations

Experimental inputs

# Uncertainty in Damping Factor: Free Cantilever



Pressure (Pa)	Mean Damping Coeff	Standard Deviation
1.11E+04	0.0025	0.00046768
2.25E+04	0.003	0.000533385
4.59E+04	0.0038	0.000670322
8.36E+04	0.0049	0.000893391



18% of mean

Inputs	PDF
Gas density	unif. & normal
Cantilever thickness $t$	unif. & normal
Cantilever width $b$	unif. & normal
Cantilever length $L$	unif. & normal
Frequency	unif. & normal

## Ranges

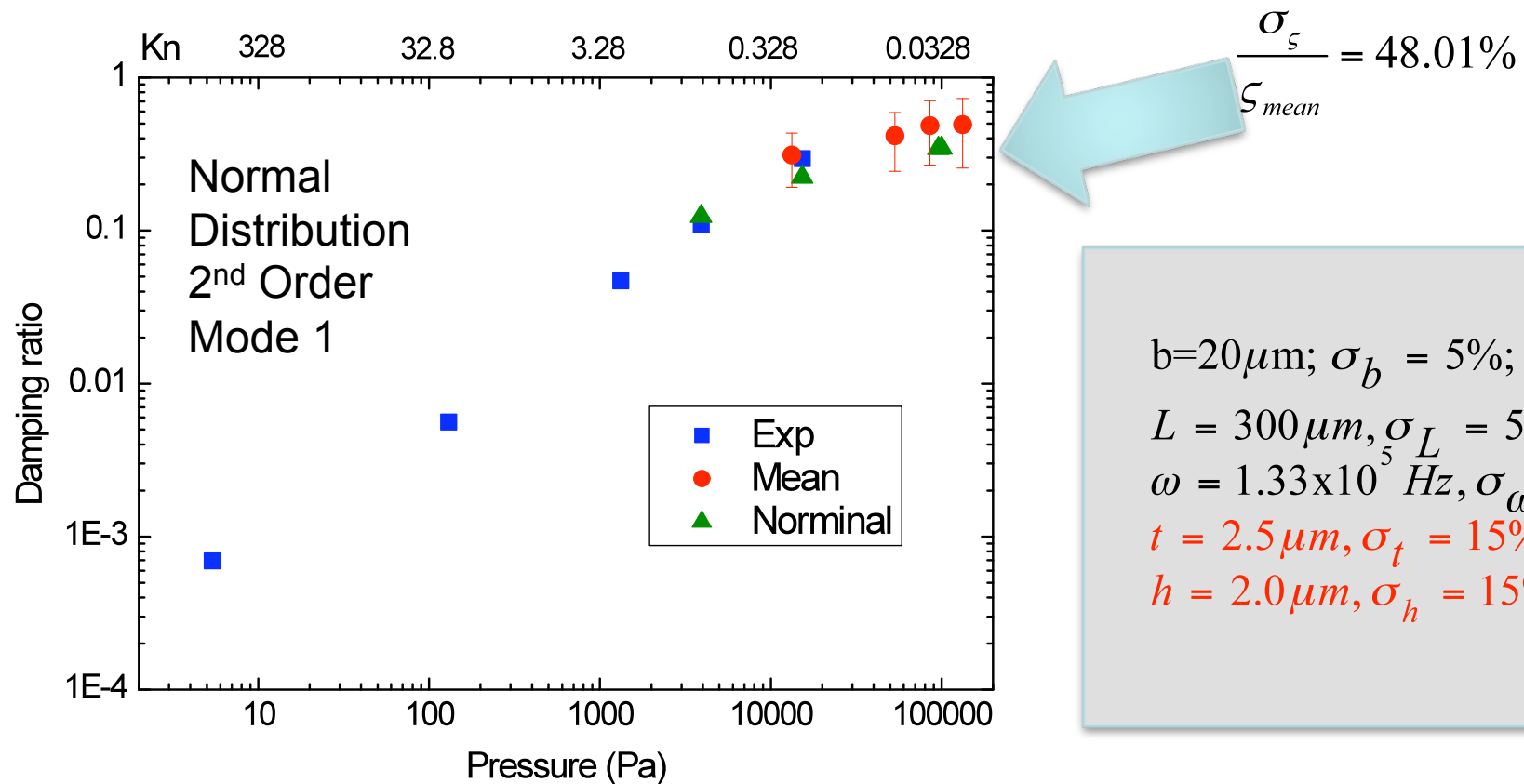
$b = 35 \mu m$ ;  $\sigma_b = 5\%$ ;  $t = 1.33 \times 10^{-5} m$   
 $\rho_g = 0.9707 kg / m^3$   
 $L = 100 \mu m$ ,  $\sigma_L = 5\%$   
 $\omega = 1.33 \times 10^5 Hz$ ,  $\sigma_\omega = 5\%$

Primary culprit is uncertainty in cantilever thickness

## Output PDF

Damping factor

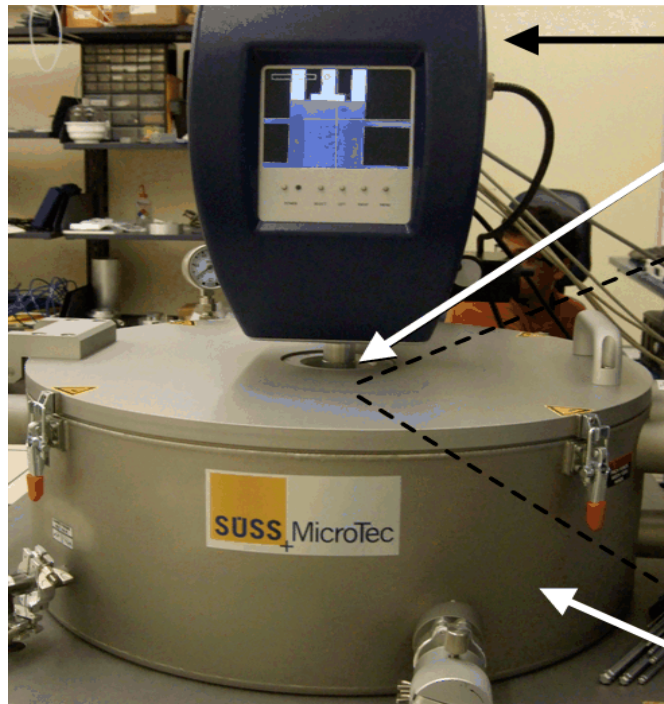
# Squeeze Film: Continuum and Slip



Experimental data from Ozdoganlar et al, Exp. Mech. 45(6), 2005.

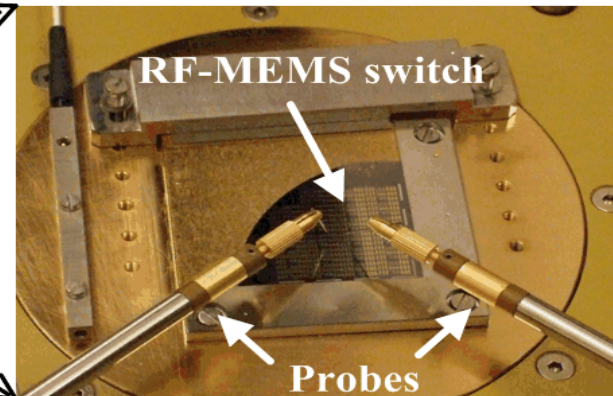
# Experimental Set-up

Facility at Purdue's Birck Nanotechnology Center



Laser Doppler Vibrometry

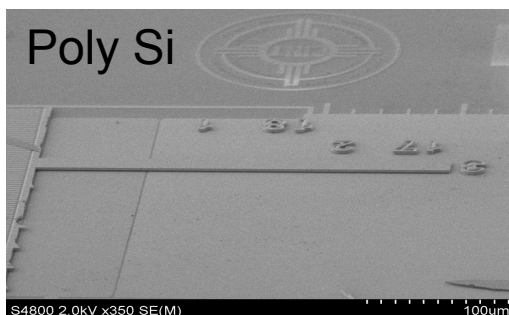
Lens



Vacuum chamber

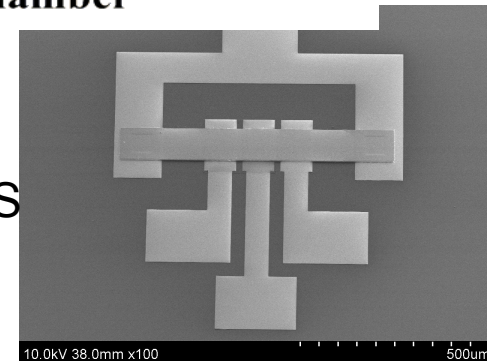
Ni membrane

Squeeze  
Film  
Cantilevers



$$l = 200 \mu m \quad b = 18 \mu m \quad t_{struc} = 2.25 \mu m \quad gap = 2.25 \mu m$$

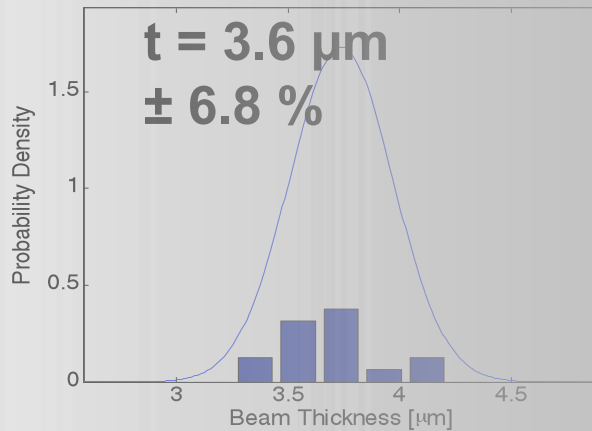
PRISM  
RF-MEMS



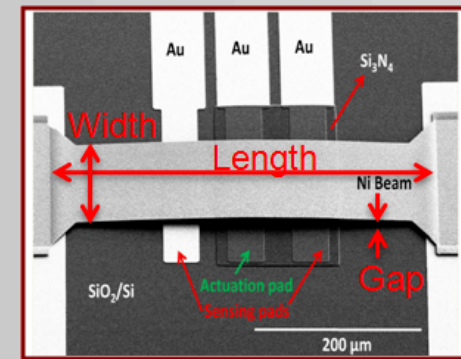
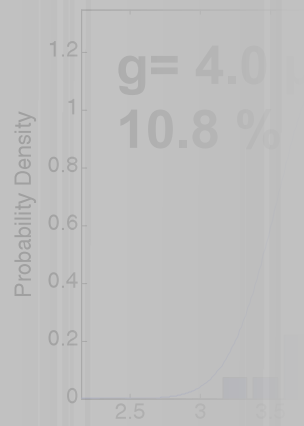
$$l = 400 \mu m \quad b = 120 \mu m \\ t_{struc} = 3 - 4 \mu m \quad gap = 3 - 4 \mu m$$

# Geometry Characterization

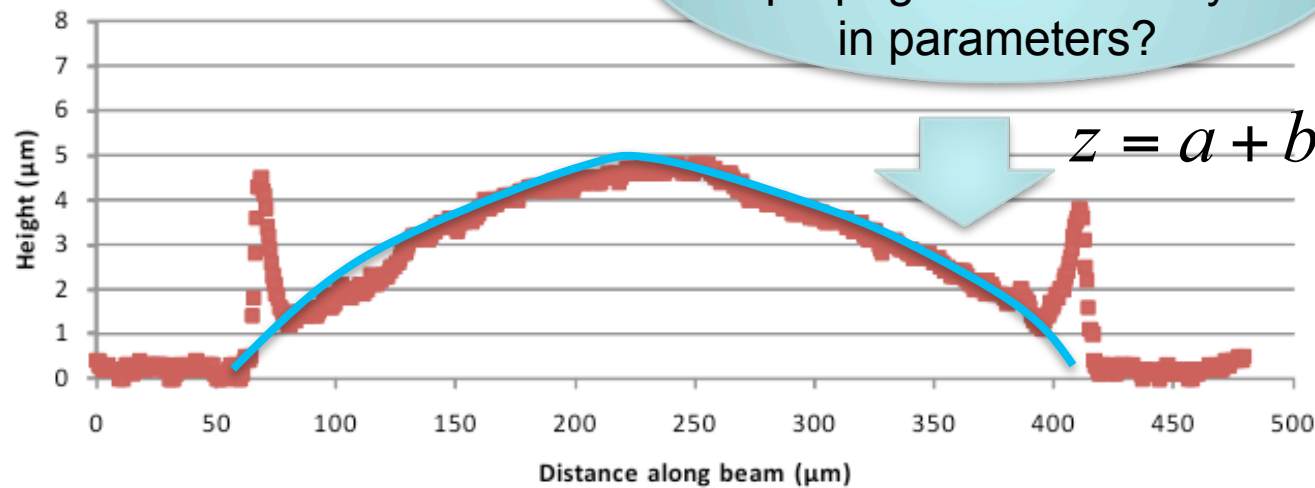
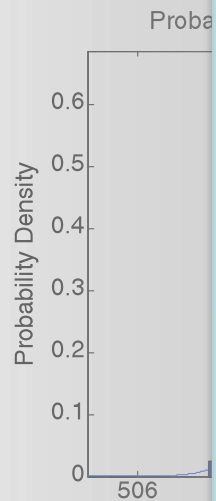
Probability Density Function of Beam Thickness



Probability Density



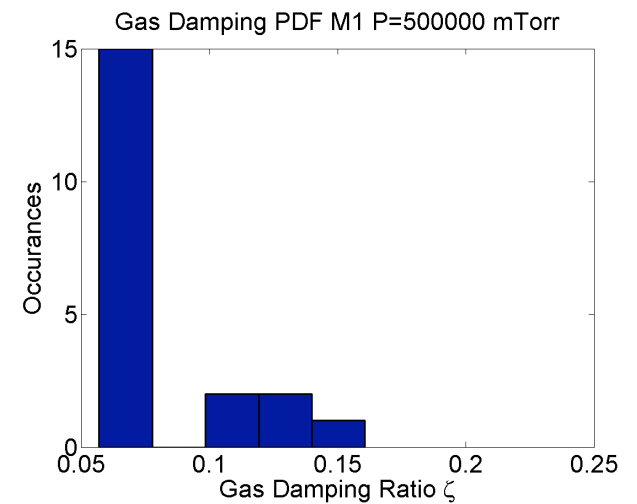
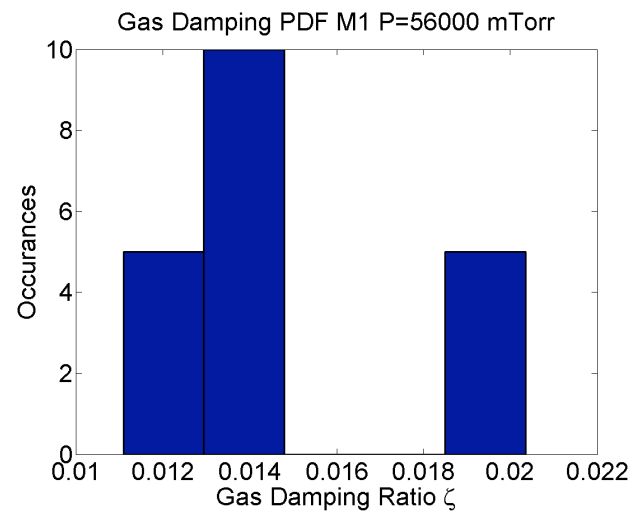
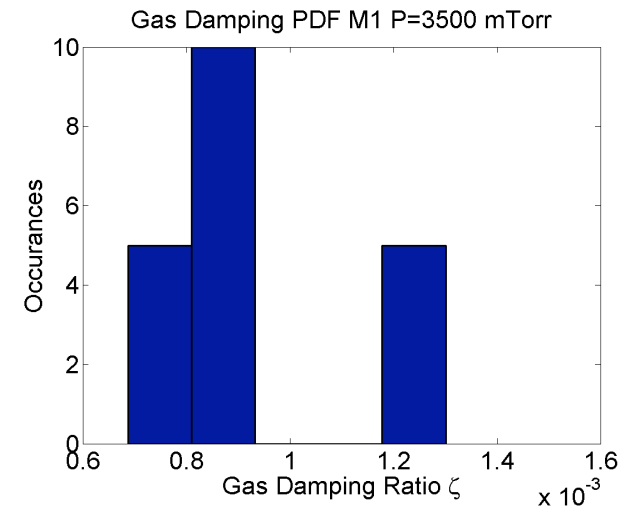
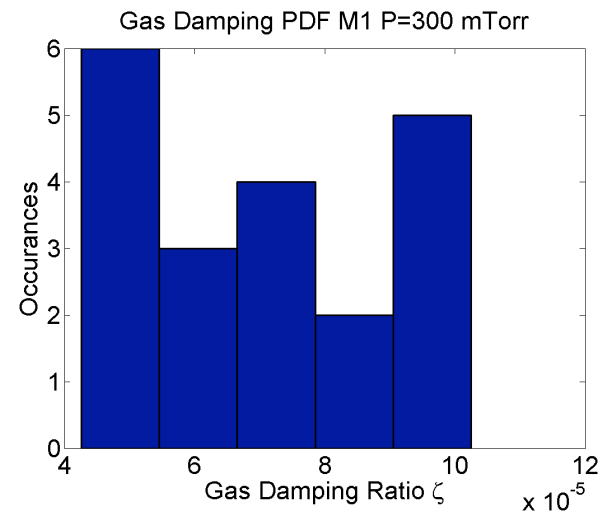
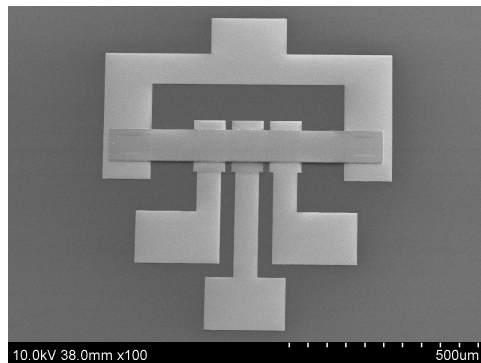
Represent in  
parametric form and  
propagate uncertainty  
in parameters?



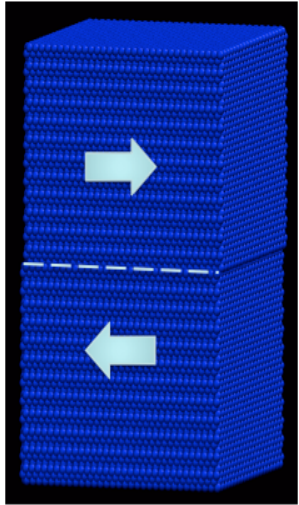
$$z = a + bx + cx^2$$

# Experimental PDFs of Damping Coefficient

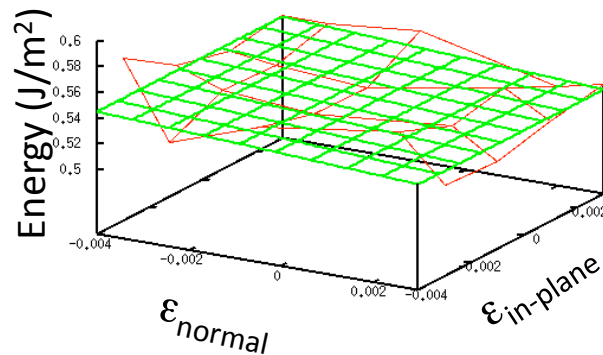
Four devices , five replicates



# Uncertainty Propagation in Multiscale Simulation

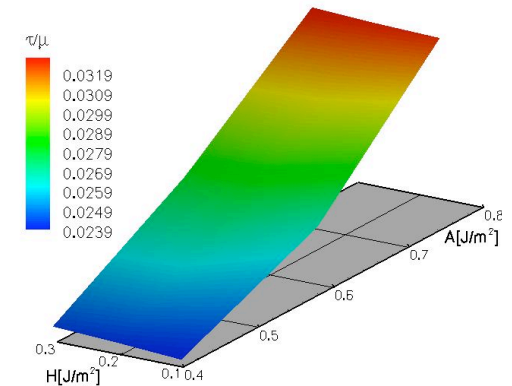
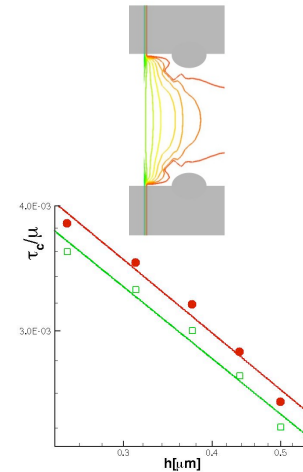


Unstable Stacking Fault Energy



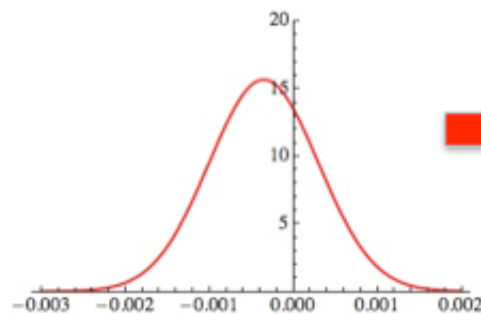
$$A[J/m^2] = 0.536 - 2\varepsilon_{normal} + 0.2\varepsilon_{in-plane}$$

Critical Resolved Shear Stress



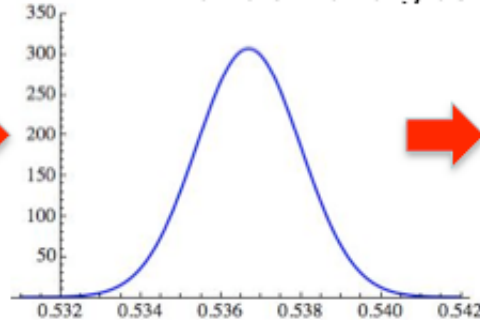
$$\tau_y/\mu = 0.01467 + 0.02117A + 0.003465H$$

PDF of internal strains



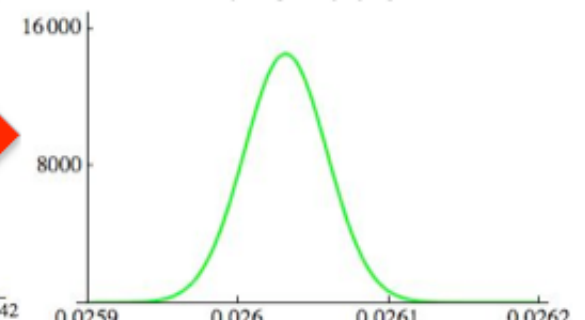
Normal strain

PDF of USF energies



USF energy (J/m²)

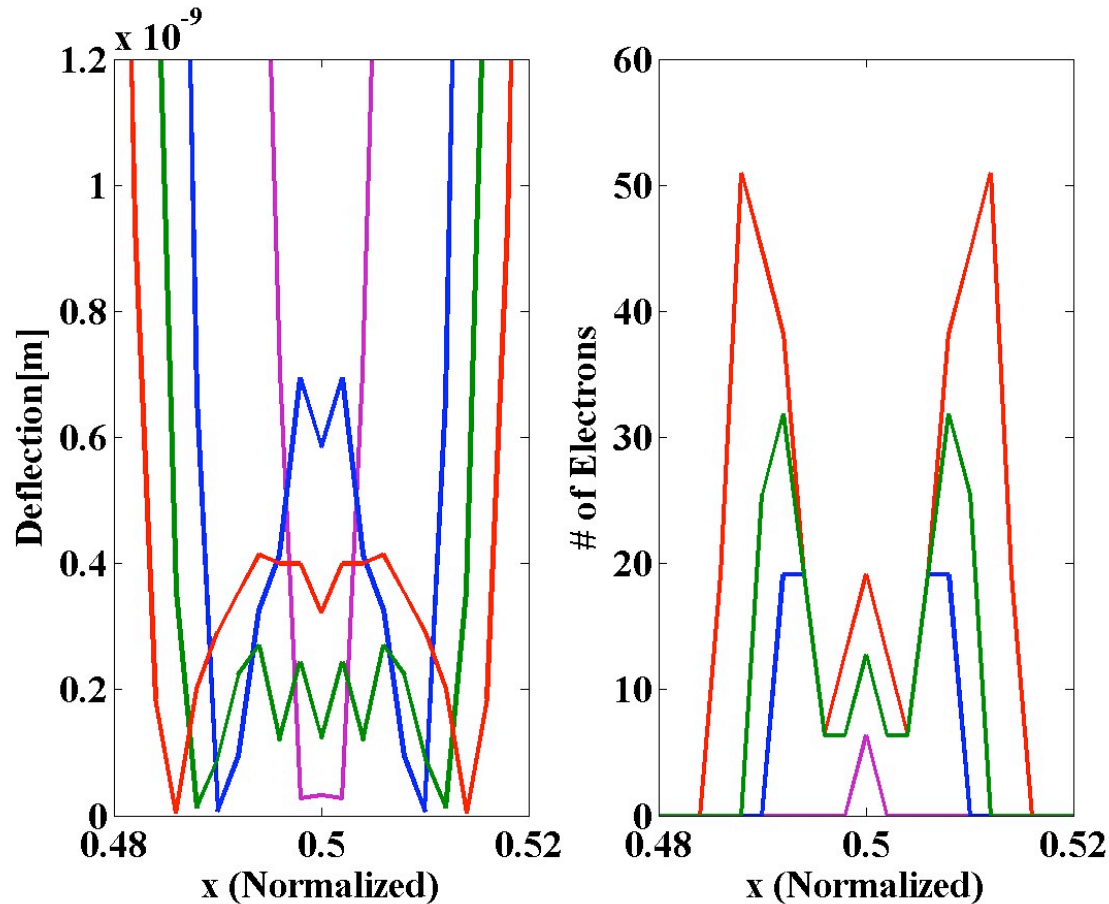
PDF of CRSS's



CRSS (μ)

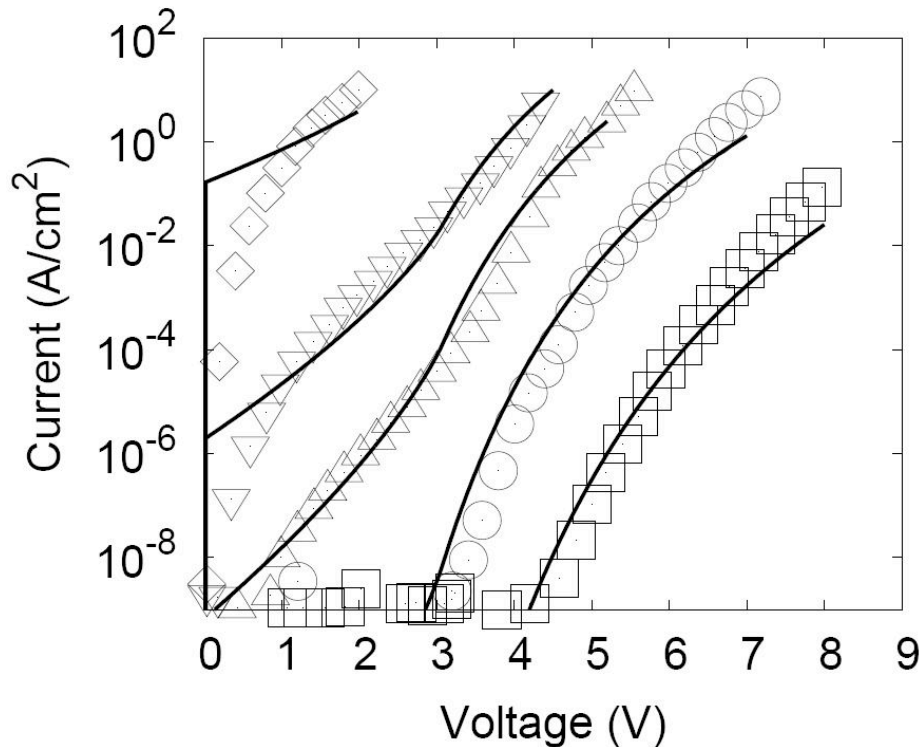
# Coarse-Grained Model: Membrane Bounce and Charge Injection

$$\rho_l \frac{\partial^2 w}{\partial t^2} = -\frac{EI}{1-\eta^2} \frac{\partial^4 w}{\partial x^4} - b \frac{\partial w}{\partial t} + F_{elec}$$

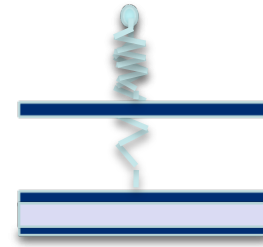


# Dielectric Charging

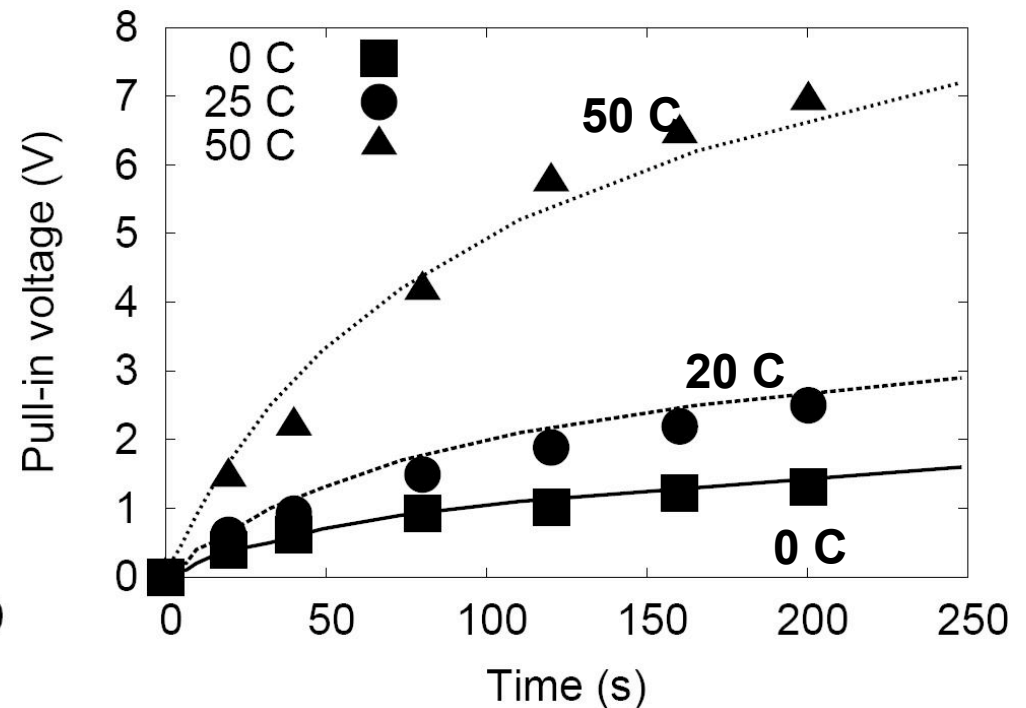
Thickness dependent  
tunneling current



*"Self-consistent simulation of quantization effects and tunneling current in ultra-thin gate oxide MOS devices" – A.Ghetti et. al.*



Charge trapping in oxides:  
theory and experiment



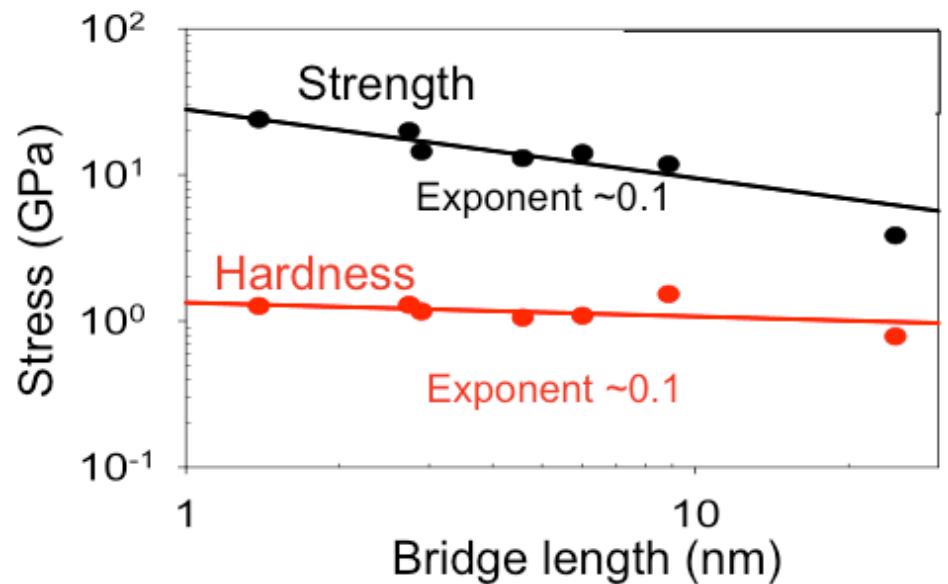
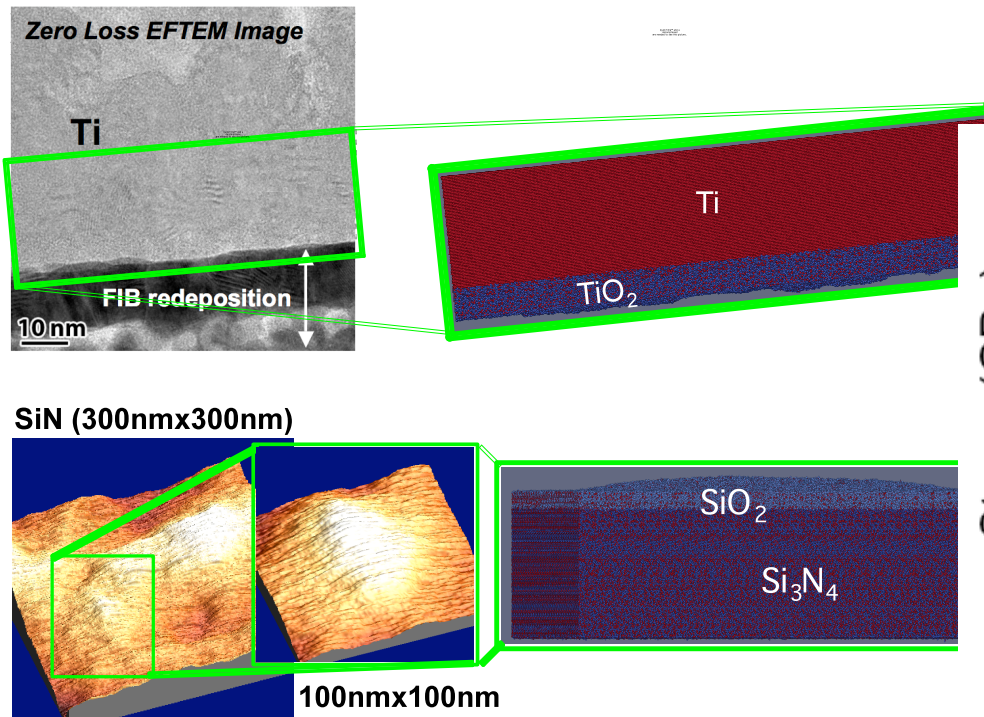
*"Temperature acceleration of dielectric charging in RF MEMS capacitive switches" – Xiaobin Yuan et. al.*

# Atomistic Contact Simulations

Goal: For a given surface chemistry & asperity predict:

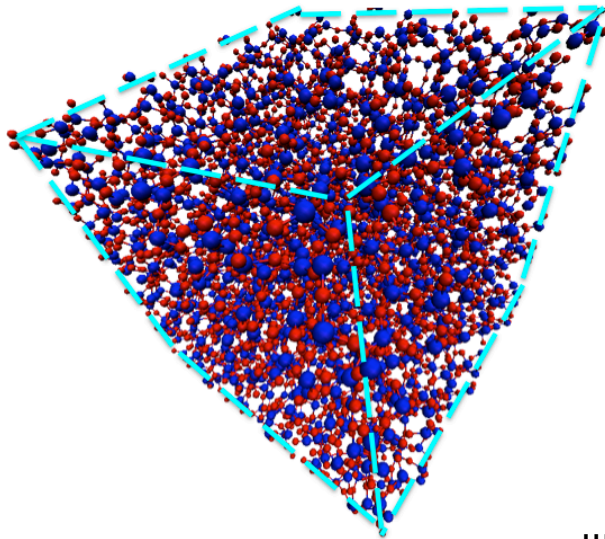
- Minimum pull-out force as a function of applied closing force?
- Sub-surface defects are generated in metal and dielectric?

Atomistic models from experimental surface roughness measurements

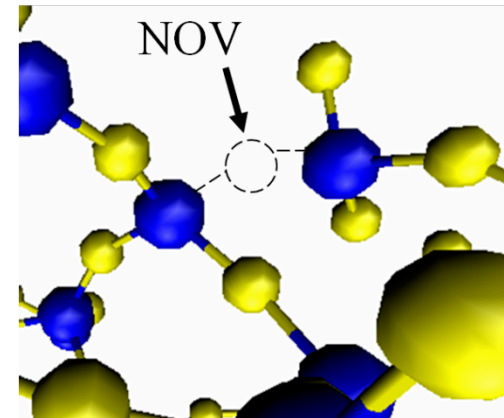
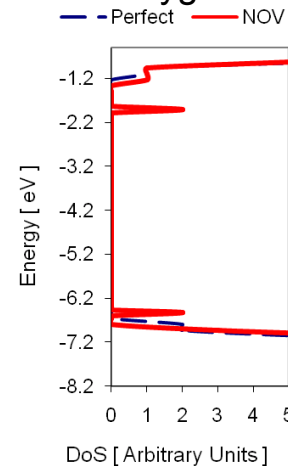


# Dielectric Charging: Atomistics

**Goal:** predict atomic structure and electronic properties of defects responsible for dielectric charging



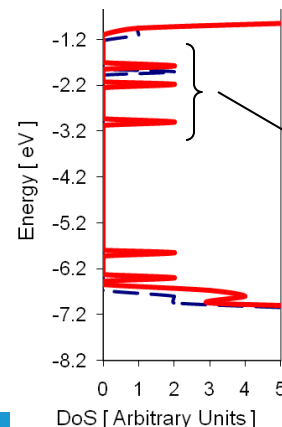
Neutral oxygen vacancy



## Approach

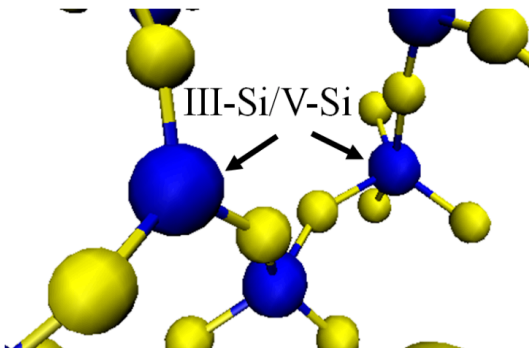
MD annealing + DFT relaxation  
& electronic properties

III-coordinated Si &  
V-coordinated Si



## Key results

- Atomistic structure of defects provide insight into defect formation process
- Electronic levels can trap charge



# What We've Learned So Far

- Geometric uncertainty characterization is critical for damping predictions
  - ...and probably for other physics as well
- Uncertainties in input geometry PDFs must be characterized
- Even with low-order cubature and sparse grid approaches, computational cost for UQ is still high
  - Use coarse system-level model to cull variables
  - Explore even simpler (linear?) models, intervals